Evaluation of Brushing as a Lunar Dust Mitigation Strategy for Thermal Control Surfaces

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Evaluation of brushing to remove lunar simulant dust from thermal control surfaces is described. First, strip brushes made with nylon, PTFE, or Thunderon® bristles were used to remove JSC-1AF dust from AZ93 thermal control paint or aluminized FEP (AlFEP) thermal control surface under ambient laboratory conditions. Nylon and PTFE bristles removed a promising amount of dust from AZ93, and nylon and Thunderon® bristles from AlFEP. But when these were tested under simulated lunar conditions in the lunar dust adhesion bell jar (LDAB), they were not effective. In a third effort, seven brushes made up of three different materials, two different geometries, and different bristle lengths and thicknesses were tested under laboratory conditions against AZ93 and AlFEP. Two of these brushes, the Zephyr fiberglass fingerprint brush and the Escoda nylon fan brush, removed over 90 percent of the dust, and so were tested in the fourth effort in the LDAB. They also performed well under these conditions recovering 80 percent or more of the original thermal performance (solar absorptance/thermal emittance) of both AZ93 and AgFEP after 20 strokes, and 90 or more percent after 200 strokes.

Nomenclature

AgFEP	=	0.25 mm (0.010 in) thick fluorinated ethylene propylene (FEP) film with a silver reflecting surface
AlFEP	=	0.13 mm (0.005 in.) thick FEP with an aluminum reflecting surface
AxFEP	=	either AgFEP or AlFEP
AZ93	=	a white thermal control paint formulated by AZ Technologies similar to Z93
α	=	absorptivity over the solar spectrum
ε	=	emissivity over thermal range (100 to 400 K)

I. Introduction

DURING the Apollo program, lunar surface operations were hampered by the effects of a fine, pervasive, highly adhesive dust. The mission records contain references to challenges involving obscuration of vision, clogging of equipment, coating of surfaces, abrasion of surfaces, degradation of seal performance, degradation of thermal performance, and minor health issues.[1] Some of the potentially most serious consequences were due to lunar dust on thermal control surfaces, which caused overheating in several of the science experiments and the batteries of the lunar roving vehicle (LRV).[2] Recent studies using lunar simulant dusts sprinkled onto thermal control surface samples in a simulated lunar environment suggest that, depending on the nature of the dust, the degradation of performance, as measured by the ratio of the solar absorptance (α) to the thermal emittance (ε), will be substantial, perhaps by as much as a factor of 3.5,[3] and unpublished data with other simulants suggest as high as 7. Increasing the thermal control surface area by such a factor is not a realistic option. It seems clear that before extensive lunar exploration efforts can continue, strategies must be developed to mitigate the effects of dust.

A wide variety of approaches have been suggested to mitigate the effects of dust. There are three principal approaches. The thermal control surface can somehow be made more dust tolerant, technology can be developed to decrease the chances of dust attaching to the surface, or technology can be developed to remove the dust from the surfaces. The technology development has generally followed one of two philosophies, active removal of the dust or prevention of its accumulation, and passive surfaces that keep the dust from adhering to the surfaces.

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Concern was raised during the Apollo program about the effect that lunar dust would have on thermal control surfaces, particularly with regard to the radiators on the LRVs which were used on the last three missions. A study was published that evaluated the effectiveness of different types of brushes in removing lunar soil and dust.[4] Using soil returned from Apollo 12, they concluded that a nylon bristle brush would be effective to remove dust from the LRV radiator, and return it to nominal function. But when the brushing was used on the LRV radiators on the lunar surface during Apollo 15, 16, and 17, it was found to be almost wholly ineffective.[2] Exactly why there was a discrepancy between the brushing effectiveness during the ground tests and the lunar surface was never explained. It is presumed that the lunar environment simulation conditions during the tests were not of sufficient fidelity.

One of the priority projects of the NASA's Exploration Technology Development Program has been to develop dust mitigation technologies to remove dust from thermal control surfaces. A logical starting place is with the technology used on Apollo, the nylon bristle brush, but using the highest fidelity lunar simulation chamber available, the lunar dust adhesion bell jar (LDAB).[5] The goal of this study was to quantify the effectiveness of the nylon bristle brush to remove dust from thermal control surfaces in the LDAB as a baseline. Five different nylon bristle brushes were tested that varied in bristle diameter, bristle length, brush configuration, and bristle packing density. In addition, four other bristle materials, PTFE Teflon, Thunderon®, fiberglass, and carbon fiber were tested for comparison. These also varied in bristle diameter, bristle length, brush configuration, and bristle packing density. Preliminary brushing effectiveness tests were run under bench-top conditions, and the most promising candidates were tested in the LDAB.

II. Methods and Materials

The brushing effectiveness tests were run as four series of experiments, which will be referred to as Stages 1 to 4. In Stage 1 initial (*ex situ*) brushing tests were carried out under ambient laboratory conditions, and the best performing brushes were tested under simulated lunar conditions (*in situ*) in the LDAB in Stage 2. The *ex situ* tests enabled a much faster turn-around, since there was no waiting to establish the vacuum and activate the dust between runs. Lessons learned during Stages 1 and 2 were applied to a second set of candidate brushes in Stage 3 *ex situ* tests. Those that performed best in Stage 3 were then tested *in situ* during Stage 4. Brushing effectiveness in the *ex situ* tests was characterized by the amount of dust removed by measuring the fraction of the thermal control surface covered by dust before and after brushing. Brushing effectiveness in the *in situ* measurements was characterized by the thermal performance, as measured by changes in the ratio of the solar absorptance (α) to the thermal emittance (ε).

Three types of thermal control surfaces were applied to 2.54 cm (1.00 in.) diameter, 0.64 cm (0.25 in.) thick aluminum substrates. The surfaces included aluminum-backed 130 μm (0.005 in.) thick FEP, 250 μm (0.010 in.) thick FEP backed with silver and an Inconel oxidation protection layer (both from Sheldahl), and AZ93 thermal control paint (AZ Technologies). In order to minimize heat losses, the substrates were suspended from the edges in the sample holder by two layers of 250 μm thick layers of Kapton®, and temperature was measured using 130 μm diameter(AWG 36) type K calibrated thermocouples affixed to the back of each sample.

The fractional dust coverage before and after the Series 1 and 3 brushing tests was determined by particle counting. Nine 1 mm^2 regions spaced about 6.3 mm apart arranged in a "+" shaped pattern, parallel and perpendicular to the brushing direction, were photographed at 100× using an optical microscope equipped with a digital camera. Each pixel was about 0.5 μm in size. This image was analyzed using ImagePro® software, sorting on color. The Series 2 and Series 4 evaluations depended not on particle counting but on thermal performance, that is, changes in α/ε. To optically determine α, The total reflectivity (ρ) of AZ93 and AxFEP samples was measured over the wavelengths of 250 to 2500 nm (where nearly all solar intensity is emitted) using either a Lambda-19 with an integrating sphere (Series 2 samples) or a Cary 5000 with an integrating sphere (Series 4 samples). The α of the AZ93 was calculated from the convolution of the ρ spectrum and the ASTM air mass zero solar spectrum. The ε of AZ93 as well as both the α and ε of the AxFEP were determined thermally from the heating and cooling curves as described below. These values are shown in Table 1. Data reported for the effectiveness of mitigation in this report is relative to these values.

Table 1. Measured values for the α and ε of pristine thermal control samples.

	α Stage 2	α Stage 4	ε Stage 2	ε Stage 4
AZ93	0.13 ± 0.01	0.171 ± 0.006	0.73 ± 0.02	0.79 ± 0.04
AlFEP	0.13 ± 0.02	-----------------	0.68 ± 0.06	---------------
AgFEP	--------------	0.095 ± 0.004	-------------	0.78 ± 0.05

The initial series of *ex situ* tests used the NASA/USGS developed lunar highlands type simulant, NU-LHT-1D. This was chosen over the more commonly used JSC-1A lunar simulant because it contains smaller particles and in handling the two lunar dust simulants it appeared that the NU-LHT-1D has higher adhesion, and so would provide a more rigorous test. Although the original test plan called for the testing of both simulants in the *in situ* LDAB tests, late in the year funding cuts shortened the tests to using one simulant. Since the *in situ* tests had already been initiated with JSC-1A, they were continued. So there is an unfortunate situation that the *ex situ* tests of Series 1 and the *in situ* tests of Series 2 to 4 were run with different lunar simulants. Although the absolute performance of the brushes is probably dependent on the lunar simulant used, it is thought that the relative performance of the brushes, and so the general conclusions of the study, are not strongly simulant dependant.

Strip brushes utilizing one of three types of bristles were used for the Stage 1 and State 2 tests, shown in Fig. 1(a). All of them were standard 0.95 cm (3/8 in.) wide brushes with a bristle length of 2.54 cm (1 in.). Nylon bristles were the baseline test, because these were judged to be effective in previous simulations, but proved to be ineffective on the lunar surface.[4] It should be pointed out, however, that both the ground simulations and the lunar environment performance was on a silica second surface mirror, which is considerably harder that either the AlFEP second surface mirror or the AZ93 white paint samples that were used in these tests.

The second type of bristle was made of polytetrafluroethylene (PTFE). Part of the rationale for this type of bristle was that the top surface of the AlFEP is chemically similar fluoroethylenepropylene (FEP) and both the Apollo suits and the current Shuttle and ISS suits have FEP outer layers. The result is that the brush and the brushing surface have the same work function, and thus electrons would not tend to flow either towards or away from the bristles. This should reduce tribocharging of the surface, which in turn would reduce the electrostatic forces which cause the dust to adhere to the surface. (This, of course, would not necessarily be the case when brushing AZ93 paint.) One complication was that the only commercially available Teflon brushes had bristles that were 1.3 mm (0.050 in.) diameter, so the brushes were very stiff.

The third type of bristle was made up of Thunderon® fibers. A brush was desired that was electrically conductive and so could drain charge from the surface. The Jacobs study had tried metallic bristle brushes and found them to be too stiff and too hard. There was concern that if a metal-coated-polymer bristle brush was used that the metal coating might come off and contaminate the thermal control surface. Although the formulation of Thunderon® is proprietary, it is a soft, conducting acrylic bristle, with no metallic coating to abrade off.

Seven different brushes were included in Stage 3 of the study. Since nylon brushes were the most effective in the initial study, a Dynasty Black Gold Fan #2 brush (FM Brushes) was selected as a nylon brush with a lower bristle packing density, and longer, thinner, more pliable bristles. A Dynasty Black Gold Fan #6 brush was selected because it has the same characteristics as the #2, but with still longer bristles. The Princeton Synthetic Watercolor Brush Series 6150 Fan #4 (Princeton Synthetic) was included because it was similar to the Gold Fan brushes, but the bristles are held into a more rigid shape by surface texture. The Escoda Toray White Synthetic Fan #6 brush was chosen because it has a variable bristle diameter, which was thought might be more effective in removing a variety of particles sizes.

In addition to the four fan brushes, three round brushes designed for fingerprint imaging were tested as well. Two Brush-N-Burnish brushes with twisted bristle packing were selected. One had carbon fibers (Brush-n-Burnish Carbosmoove II Brush) and the other glass fibers (Brush-n-Burnish Twisted Fiberglass Brush). The last fingerprint brush, Lightning Powder Fingerprint Brush (Zephyr) has fiberglass fibers that are bundled. Table 2 describes the characteristics of the brushes tested, and Fig. 1(b) shows them in a photograph.

Figure 1. Brushes used in the Stage 1 study (left): (a) nylon, (b) PTFE, and (c) Thunderon®. Brushes used in the Stage 3 study (right): (d) B&B Carbon, (e) Black Gold Fan #2, (f) B&B Glass, (g) Black Gold Fan #6, (h) Locked Fan #4, (i) Zephyr Lightning, (j) Escoda Fan #6.

Table 2. Characteristics of brushes used in this study

Brush	Material	Geometry	Length, cm	Bristle diameter, μm	Bristle packing
Nylon strip	Nylon	Strip	2.5	300	Twisted
PTFE strip	PTFE	Strip	2.5	1300	Straight
Thunderon® strip	Thunderon®	Strip	2.5	30	Straight
Black Gold #2	Nylon	Fan	1.5	35-50 w/taper to 5	Straight
Black Gold #6	Nylon	Fan	2.5	35-50 w/taper to 6	Straight
Locked Fan #4	Nylon	Fan	2.8	32 - 45	Locked
Escoda Fan #6	Nylon	Fan	2.6	35	Straight
B&B Carbon	Carbon	Round	6.0	10	Twisted
B&B Glass	Fiberglass	Round	5.0	35 - 40	Twisted
Zephyr Lightning	Fiberglass	Round	5.7	15	Bundled

A rotational motion was used in all of the brushing tests. Figure 2 shows the samples and both the *ex situ* and *in situ* brushing apparati. The initial tests used a rotational speed of 2 strokes/s, but brushes used in Stages 3 and 4 were physically larger which lead to an increased torque resistance. For the *ex situ* trials only, the rotation frequency was doubled to 2 cycles/s (4 strokes/s) to enable the motor to run smoother. The faster rate in combination with the longer lever arm resulted in a tangential velocity of the brush that was a factor of 4× to 8× greater than that of the previous tests. However, a parameterization study found that dust removal was insensitive to the speed of the brushing, at least through a factor of 10, so the results of the two test series should be comparable. For the Stage 1 trials, *ex situ* trials were carried out for 20, 60, 200, 600, and 2000 strokes at 2 strokes/s, and the Stage 2 *in situ* trials for 1000 strokes at 2 strokes/s. But the Stage 3 test series, *ex situ* trials were carried out for 40, 120, 400, 1200, and 4000 strokes at 4 strokes/s, and for the Stage 4 *in situ* trials for 20 and 200 strokes at 2 strokes/s.

The *in situ* tests were conducted in the LDAB. To start, the JSC-1AF, with a maximum particle size of 20 μm, was placed in the LDAB and treated with an air plasma to remove organic residue from the grains. It was subsequently dried by heating to 200 °C *in vacuo* for 12 to 24 hr, and then treated with a hydrogen-helium plasma to chemically reduce their surfaces. Heating and cooling curves were obtained by shining a 10-sun xenon arc lamp on each sample individually and then letting them cool in a 30 K cold-box. The heating and cooling curves for each sample was measured in the pristine state, after being dusted, and after being brushed. The curves were then analyzed using Thermal Desktop® (Cullimore and Ring Technologies) to extract the α and ε. Particle counting was carried out on 50 of 641 randomly chosen non-overlapping viewing frames in an optical microscope at a magnification of 100× and analyzed using ImagePro® software. The procedures are described in detail elsewhere.[6]

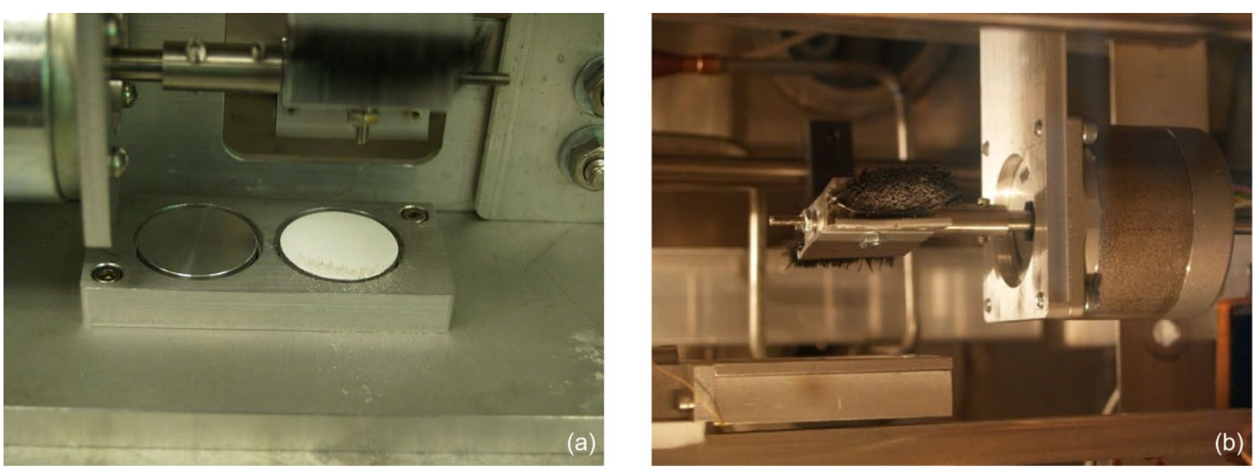

Figure 2. Photographs of the (a) *ex situ* brushing test and (b) *in* situ brushing test apparati.

III. Results and Discussion

A. Stage 1: Initial Bench Top Testing

1. Nylon Bristle Brush Tests

The first test was to determine if, for a given number of brush strokes, the speed of the brushing was an important variable. Tests were conducted on the AZ93 sample, with the assumption that the AxFEP behavior would be similar. Two different speeds were used, about 3.8 strokes/s and about 38.7 strokes/s. Each of these was carried out for three different time intervals to give 385, 3850, and 38,500 strokes. Within these limits, brushing speed was found to not affect the amount of dust removed.

Figure 3 shows the fraction of 1 mm^2 sampling area covered by NU-LHT-1D lunar simulant dust in the line across the sample perpendicular to the brushing direction. Data parallel to the brushing direction were similar except at the extremes where the brush did not make full contact with the sample. Each data point is the average of 20, 60, 200, 600, and 2000 strokes by the nylon strip bristle brush. There was no particular trend of the dust removal over time, indicating that after 20 strokes steady state between dust removal and deposition by the brush had been established. The error bars on Fig. 3 represent 1σ in the spread of 4 to 8 data points. Comparison with Fig. 3(a) and (b) shows that the nylon brush was more effective at removing the dust from the AZ93 paint than the AlFEP. In the case of AZ93 taking the total data set gave an average of 0.084 ± 0.089 of the surface still covered with dust. But it can be seen that the edges of the brush were not as effective, probably due to the distortion of the shape as the bristle moves across the surface. Bristles near the center of the brush are constrained to flex in the direction of motion by neighboring bristles, but those near the ends can also flex outward, and so apply less force to the surface. On average 0.33 ± 0.17 of the AgFEP surface was covered with dust after brushing. There is no discernable rise in the amount of dust remaining on this sample near the edges, perhaps because the brush embedded dust grains into the surface rather than flicking them off. In both the AZ93 and the AlFEP most of the dust that remained on the surface was left in streaks. It was also noted that both the FEP and AZ93 paint surface was rather deeply scratched after this test (Fig. 4). Since nylon is relatively soft, particularly compared to the AZ93, these were probably caused by dust adhering to the bristles and then gouging into the surface.

2. PTFE Bristle Brush Tests

Figure 5 shows the fraction of the sampling area covered by dust after brushing the AZ93 and AlFEP samples with the PTFE brush. The dust coverage on the AZ93 was reduced to 0.25 ± 0.14. But 2 of the 36 data points, the 20 stroke data from position-4, and the 200 stroke data at position 0, appear to be anomalously high, apparently skewing the results. If those two points are dropped from the analysis then the dust coverage on the AZ93 was reduced to 0.22 ± 0.07, which is probably more indicative of the PTFE effectiveness. In contrast, the PTFE brush left 0.86 ± 0.18 of the AlFEP surface covered with dust. In this case nearly two-thirds of the sampling regions had dust coverage greater than 0.9, indicating very limited effectiveness in the ability to remove dust from the FEP surface with this brush. Owing to the large diameter of the PTFE bristles, they had little flexibility. This caused them to damage the surface more, and be less effective in removing the dust. Instead, this brush just embedded the dust into the soft FEP surface.

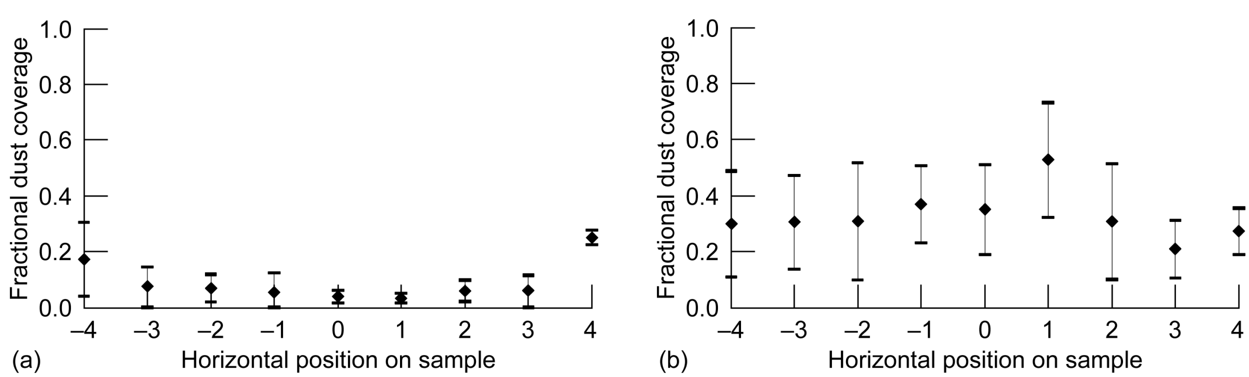

Figure 3. The mean and standard deviation of fraction of dust remaining on the surface of the (a) AZ93 paint and (b) AlFEP after being brushed in the *ex situ* bench-top test with the nylon bristle brush.

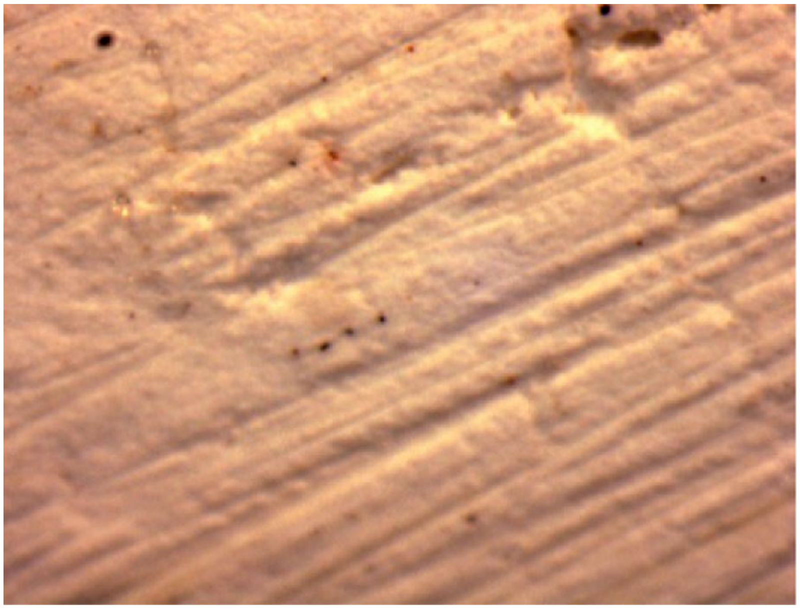

Figure 4. Abrasion lines are clearly visible in this 100× photomicrograph of AZ93 that has been brushed with a nylon bristle brush.

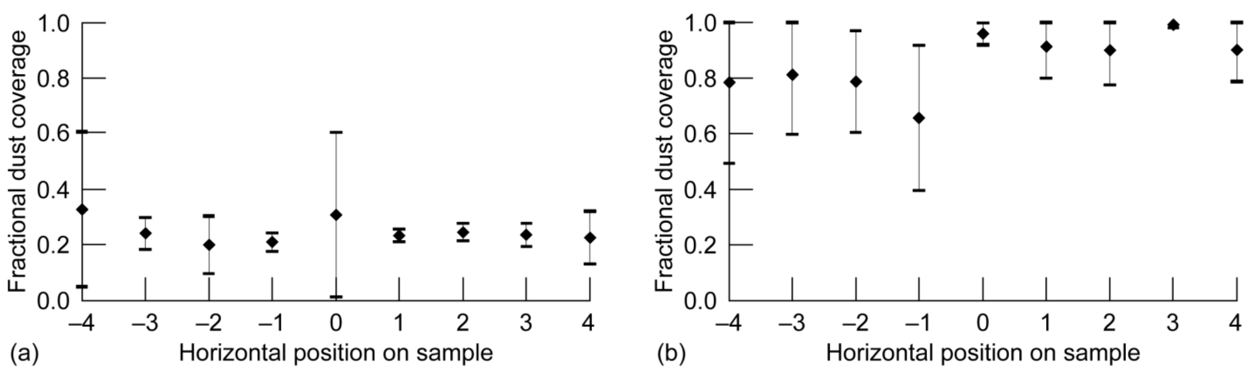

Figure 5. The fraction of dust remaining on the surface of the (a) AZ93 paint, and (b) AlFEP after being brushed in the *ex situ* bench-top test with the PTFE bristle brush.

3. Thunderon® Bristle Brush Tests

The effectiveness of the Thunderon® brushes to remove dust from the thermal control surfaces is shown in Fig. 6. The brush left 0.39 ± 0.11 of the AZ93 surface covered with dust. In addition, at the end of the test there were many bristle fragments on the paint, which visibly darkened the surface. The brush was also visibly damaged, with the bristle length being shorter and many of the bristles were curled. This abrasion would make the Thunderon® unsuitable for use with the AZ93 paint. However, the Thunderon® brush worked well to remove dust from the AlFEP. The brush left just 0.13 ± 0.11 of the surface covered with dust, with over half of the sample areas being less than 0.1 covered in dust. Although the soft bristles still seemed to scratch the surface of the AlFEP, dust did not get embedded into the scratches. Thunderon® was the only brush tested in Stage 1 that effectively removed dust from the AlFEP in the *ex situ* bench-top tests.

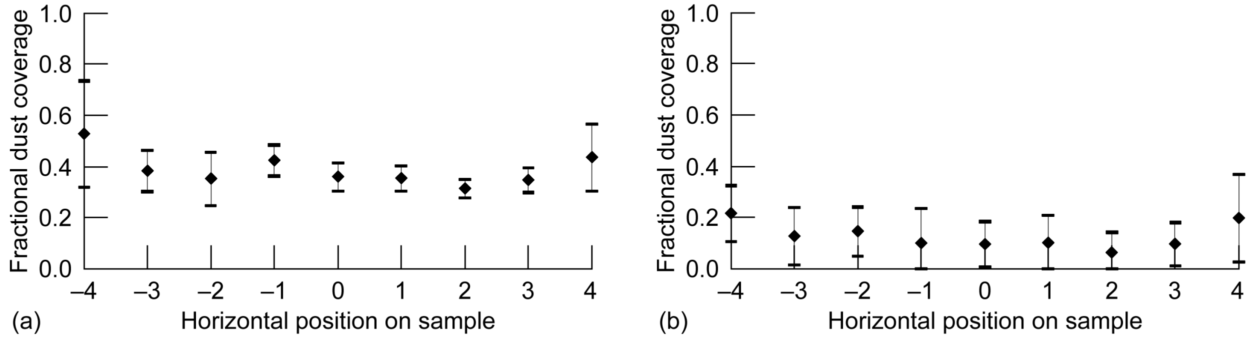

Figure 6. The fraction of dust remaining on the surface of the (a) AZ93 paint, and (b) AlFEP after being brushed in the *ex situ* bench-top test with the Thunderon® bristle brush.

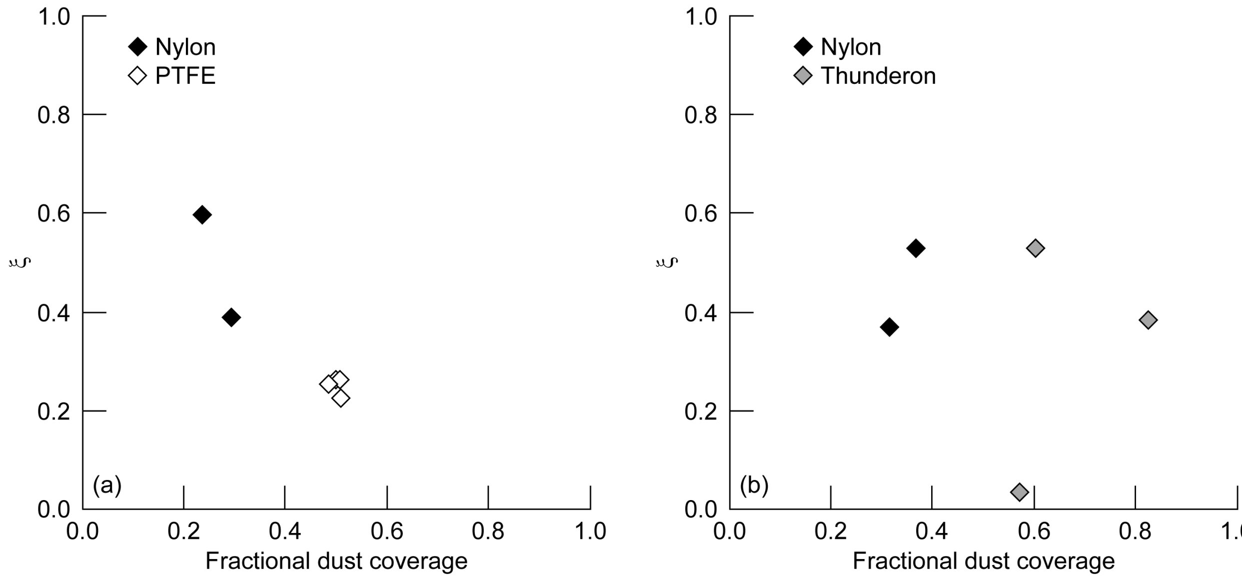

Figure 7. Dust clearing parameter, ξ, as a function of initial fraction of the thermal control surfaces covered with JSC-1A lunar simulant dust for (a) AZ93, and (b) AlFEP.

B. Stage 2: Initial LDAB Testing

For these tests there was an attempt to apply relatively heavy dust coverage to more fully test the brushing. Although the fractional dust coverage was not measured directly, the α and ε of the JSC-1AF dusted samples were measured. Using previous results, the value of α/ε could then be used to calculate the approximate fractional dust coverage before brushing using the equation of the least squares fit from our previous work.[3]

One measure of effectiveness of a cleaning technique compares the ratio of the integrated solar absorptance to the integrated thermal emittance (α/ε) of the surface after it has been brushed off $(\alpha/\varepsilon)_b$ to the α/ε of the dusted surface $(\alpha/\varepsilon)_d$ in terms of the that of the pristine surface $(\alpha/\varepsilon)_p$. A new term, the dust removal efficiency, ξ, is defined in Equation (1) as:

$$\xi \equiv \frac{(\alpha/\varepsilon)_d - (\alpha/\varepsilon)_b}{(\alpha/\varepsilon)_d - (\alpha/\varepsilon)_p} \quad (1)$$

Inspection of this equation reveals that if no dust is removed, that is $(\alpha/\varepsilon)_b = (\alpha/\varepsilon)_d$ then $\xi = 0$. If all of the dust has been removed, $(\alpha/\varepsilon)_b = (\alpha/\varepsilon)_p$ then $\xi = 1$. Previous studies have shown that a complete monolayer of JSC-1AF lunar simulant increases the α/ε of a thermal control surface by about a factor of 3.5.[3]

The effect of brushing JSC-1A from AZ93 by the nylon and PTFE brushes on the α and ε of the surface, as expressed by ξ is shown in Fig. 7(a). Dust deposition raised the α of the AZ93 substantially, by about a factor of 3. Brushing with either nylon or PTFE lowered the α slightly. So even though both brushes were very effective in removing dust from the AZ93 under ambient conditions, under simulated lunar conditions they lost their effectiveness. Neither of the brushes in these tests would be effective at removing enough dust to substantially lower the α once dusted.

Figure 7(b) shows the effects of dusting and brushing on the ξ of the AlFEP surface. The JSC-1A dust increased the α of the AlFEP by about a factor of 2. As with the AZ93, the nylon bristle brush restored about half of the thermal performance. Two of the samples showed a similar clearing by the Thunderon® bristle brush, and the third was not cleared. As with the AZ93, brushes that were effective at removing dust under ambient conditions were ineffective at restoring thermal performance under simulated lunar conditions. Neither of these brushes was judged to be effective enough to warrant further investigation.

Even though the results of the brushing tests under simulated lunar conditions were not promising, and despite the fact that the nylon bristle brush used during Apollo were almost totally ineffective when used on the LRV radiators, brushing is such a simple solution that further trials seemed warranted. Evidence of abrasion of the thermal control surfaces lead to the consideration that perhaps more flexible bristles would be more effective. This lead to the decision to conduct a second round of testing with a variety of bristle materials, lengths, diameters, and packing geometries.

C. Stage 3: Advanced Benchtop Brushing

Fractional coverage diagrams such as those shown in Figs. 3, 5, and 6 were generated for each of the seven brushes selected for the advanced brushing study. Since the samples were not uniformly covered with dust at the start of the tests, the total dust remaining after the test is not indicative of brush performance. Instead a dust clearing parameter (Ξ) was used to judge brush performance, defined in Equation (2) as:

$$\Xi = \frac{(\%\text{dust coverage})_{\text{before}} - (\%\text{dust coverage})_{\text{after}}}{(\%\text{dust coverage})_{\text{before}}} \tag{2}$$

The average Ξ for AlFEP samples brushed with each of the seven brush types are plotted in Fig. 8. Two brushes, the Escoda Fan and the Zephyr Round met the success criteria of cleaning off 90 percent of the dust ($\Xi = 0.9$) and three others were effective enough ($\Xi > 0.8$) to warrant future consideration, especially considering the spread in the measurements. The bars shown in red were fan brushes and those shown in blue were round brushes. It appears that either geometry can make for an effective brush.

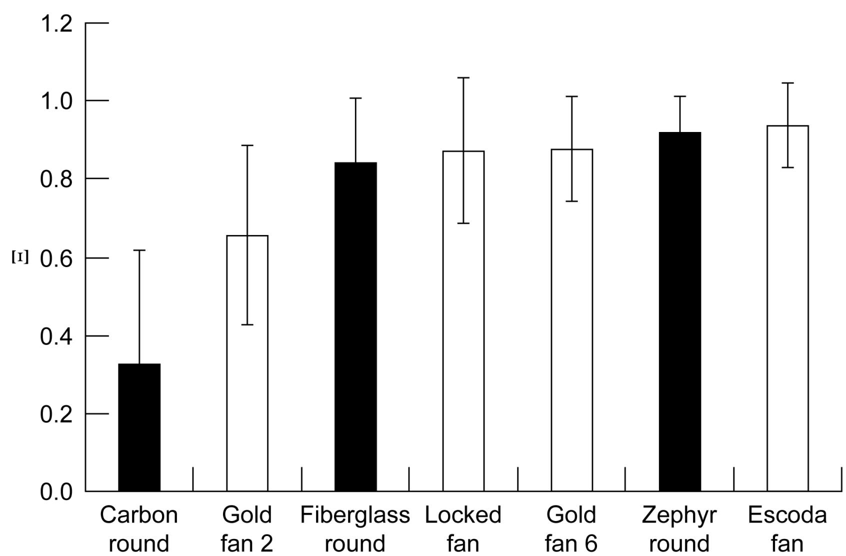

Figure 8. Average values of Ξ for each of the seven brush types. Error bars represent ± 1σ. Bars shown in white were fan brushes and those found in black were round brushes.

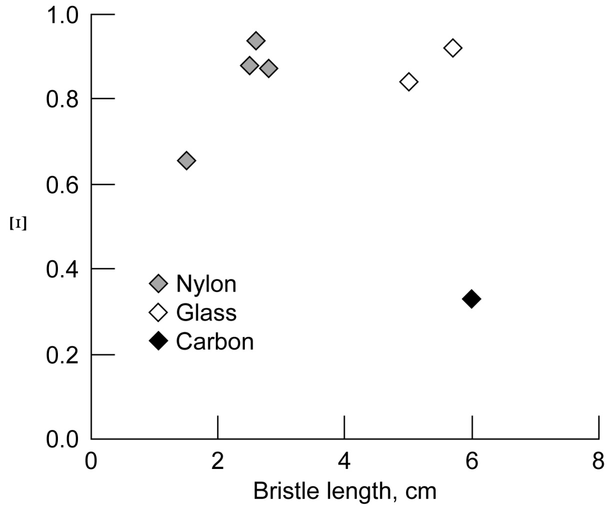

Figure 9. Average values of Ξ as a function of bristle length for each of the seven brush types. Bristle material is indicated by color.

Two new bristle materials were introduced in this study that were not included in the initial study, fiberglass and carbon. Figure 9 shows Ξ for the brushes sorted by bristle material. Although there was only one carbon bristle brush tested, it had by far the poorest performance. The fiberglass bristles, on the other hand, had performance comparable to the nylon bristles. Fiberglass is also likely to be more durable in the high radiation environment of the lunar surfaces than nylon. All of the brushes used in this study had longer bristles than those used in the initial study, and since they also performed better, it is worth exploring how important bristle length is. This relationship is also shown in Fig. 9, which shows a plot of Ξ as a function of bristle length. This reveals that bristle length is certainly not an overriding factor in that the longest bristles were on the least effective brush, and the shortest on the second least effective. However, within similar brushes, length appears to play a role. This is seen most directly by comparing the Gold Fan #2 and the Gold Fan #6 performance (Fig. 8). These two brushes were identical except for bristle length and the #6 had an average Ξ of 0.88 compared to the #2 average Ξ of 0.65 (see Fig. 4). There may also be an upward trend in Ξ with bristle length within the nylon fan brushes and within the fiberglass round brushes.

There were only four AZ93 painted samples available for these tests, so they were tested with only the top two performing brushes, the nylon bristled Escoda fan brush and the fiberglass bristled Zephyr round brush. They were tested at 30 s and 300 s intervals (120 and 1200 strokes). Both brushes were very effective at removing the dust, leaving less that 0.5 percent of the surface covered ($\Xi > 0.995$).

D. Stage 4: Advanced LDAB Brushing

By particle counting, both the Zephyr and the Escoda brushes were more effective at removing dust from the AZ93 painted surfaces than from the AgFEP surfaces. Although there was a wide variation, the AZ93 surfaces brushed 200 strokes with a Zephyr brush had an average of 3 percent of its surface covered with dust and with the Escoda had 10 percent covered. The AgFEP surface on the other hand was on average 29 percent covered when brushed by the Zephyr and 31 percent covered when brushed by the Escoda. Thus, they removed dust from AgFEP with equal efficiency, but the Zephyr brushed removed dust from the AZ93 surface more efficiently.

Figure 10 shows ξ as a function of the relative α/ε of the samples after they were dusted but before they were brushed, where $(\alpha/\varepsilon)_{rel} = (\alpha/\varepsilon)_{dust}/(\alpha/\varepsilon)_{pris}$. For AZ93 samples brushed with the Zephyr brush and the Escoda brush, the spread in the data is wide, about a factor of 2. But the mean ξ values for the two brushes are statistically indistinguishable, 0.8 for 20 brush strokes and 0.9 for 200 brush strokes. With the Zephyr brush there is no trend in ξ with the initial amount of dust. That means that on average enough dust is removed in 20 strokes to increase the α/ε to 80 percent of its pristine value regardless of whether the initial α/ε was degraded by a factor of 2 or a factor of 4. There appears to be a trend with the Escoda brush that ξ increases with the initial amount of dust. That is to say, the Escoda brush returns the α/ε towards pristine values more rapidly if there is more dust initially on the AZ93.

Figure 11 shows ξ as a function of the relative α/ε of the samples after they were dusted but before they were brushed for AgFEP samples brushed with the Zephyr brush and the Escoda brush. The Zephyr brush data look similar to the AZ93 data. The spread in ξ is about a factor of 2, with the average after 20 strokes being about 0.8 and

after 200 strokes about 0.9. But the ξ values for the Escoda brush data are considerably different. The spread is only about 10 percent, and the average ξ after 20 strokes is 0.92 and after 200 strokes is 0.95. But it is also worth noting that the Escoda-brushed AgFEP samples started with a heavier coating of dust. The α/ε after dusting ranged from 4.4 to 7.4, whereas that which was Zephyr brushed ranged from 2.5 to 4.2. As noted above, heavier dust loads are removed relatively more quickly with the Escoda brush.

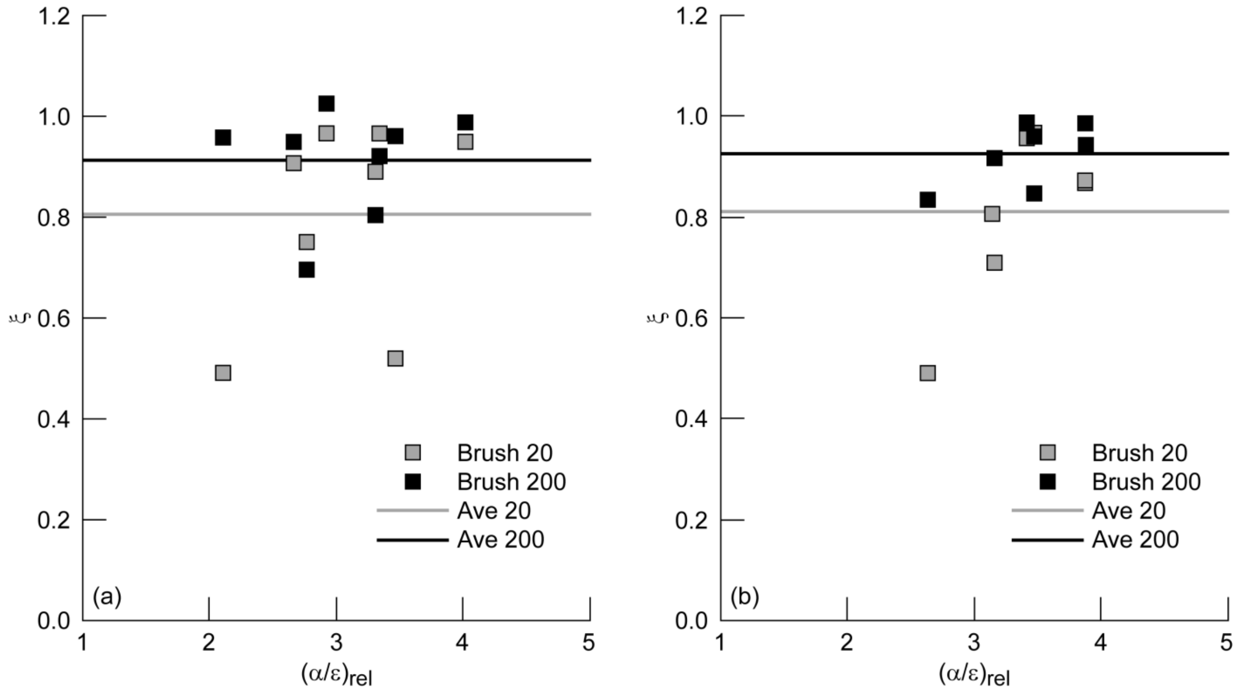

Figure 10. The values of dust removal efficiency, ξ, as a function of relative α/ε for the (a) Zephyr and (b) Escoda brushes for JSC-1AF simulant on AZ93.

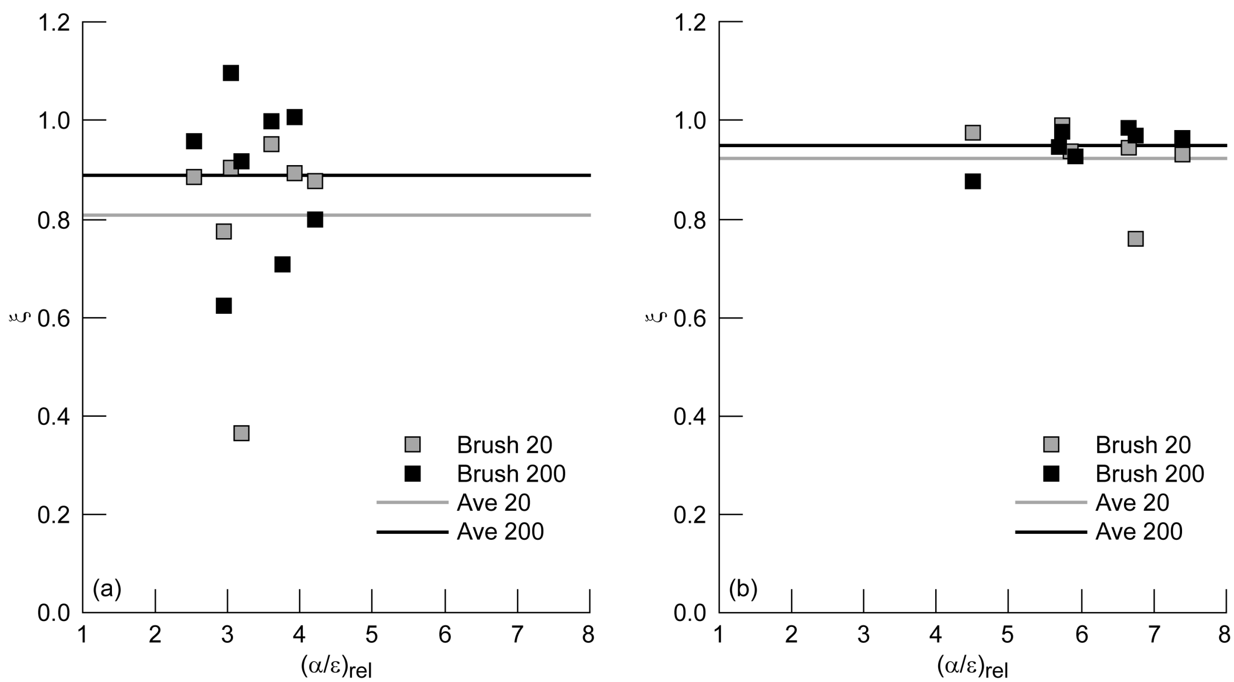

Figure 11. The values of dust removal efficiency, ξ, as a function of relative α/ε for the (a) Zephyr and (b) Escoda brushes for JSC-1AF simulant on AgFEP.

Although ξ is a useful parameter to judge the relative effectiveness of brushes, ultimately what is important is the final value of the thermal control surface after the dust layer has been cleaned from it. Table 3 shows the actual mean α/ε values for the pristine samples used in a particular series of tests and those of the dusted and cleaned samples. Even though there was much more dust left on the AgFEP samples in the end the thermal performance of the dusted and brushed sample still out performed the AZ93 samples by a factor of 1.6 to 1.9.

Table 3. Values of α/ε for thermal control surfaces in the pristine state, dusted, and dusted then brushed 20 or 200 strokes by either the Zephyr or Escoda brush.

	$(\alpha/\varepsilon)_{pris}$	$(\alpha/\varepsilon)_{dust}$	$(\alpha/\varepsilon)_{B20}$	$(\alpha/\varepsilon)_{B200}$
Zephyr brushed AZ93	0.22	0.65	0.30	0.26
Escoda brushed AZ93	0.21	0.70	0.29	0.24
Zephyr brushed AgFEP	0.12	0.40	0.21	0.15
Escoda brushed AgFEP	0.10	0.61	0.14	0.13

IV. Conclusions

A four stage investigation into the effectiveness of brushing of thermal control surfaces was undertaken. In Stage 1, strip brushes of three bristle types were used to remove NU-LHT-1D lunar simulant from AZ93 and AgFEP thermal control surfaces under ambient laboratory conditions. The nylon bristle removed more than 90 percent of the dust and PTFE bristle removed nearly than 80 percent of the dust from AZ93, as determined by particle counting. The Thunderon® bristle brush was ineffective. On the AlFEP surface, the Thunderon® bristle brush removed more than 90 percent of the dust, and the nylon bristle removed two-thirds of the dust, and the PTFE bristle brush was ineffective. In Stage 2, none of the brushes proved to be effective under simulated lunar conditions. A nylon bristle brush was not very effective in restoring the α of thermal control surface on the Apollo LRV, so perhaps it is a validation of the fidelity of our lunar simulation facility and protocol that the brushing was not effective, as opposed to the study of Jacobs[1] that indicated it was effective.

In Stage 3 of the investigation seven additional brushes made up of three materials, two brush designs, and seven bristle lengths were tested for their effectiveness to remove dust from thermal control surfaces under ambient laboratory conditions. The carbon bristle brush was found to be ineffective, but fiberglass and nylon brushes were found to be equally effective. Both the fan brush and round brush designs proved to be more effective that the strip brushes tested in the first stage. Longer bristles were found to be more effective at removing dust than shorter bristles, though the effect seems less important than brush material. Two brushes, the nylon Escoda fan brush and the round fiberglass Zephyr brush removed more than 90 percent of the dust from AlFEP surfaces under ambient conditions, with a few as 40 strokes. Both brushes were also able to remove more than 99.5 percent of the dust from AZ-93 thermal control paint with as few as 120 strokes.

In Stage 4 the Zephyr and Escoda brushes were tested for their effectiveness at removing lunar simulant dust from thermal control surface materials under simulated lunar conditions. Both proved effective, restoring more than 80 percent of the pristine α/ε for both thermal control surfaces after 20 strokes, and more than 90 percent after 200 strokes. The Escoda brush performed slightly better than the Zephyr on AgFEP, though perhaps within the error of the experiment. Although the brushes removed more dust from the AZ93 surfaces than from the AgFEP surfaces, the dusted-then-brushed AgFEP surfaces still out performed the dusted-then-brushed AZ93 surfaces, when judged by α/ε. Both brushes were judged effective at removing dust and restoring optical properties.

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